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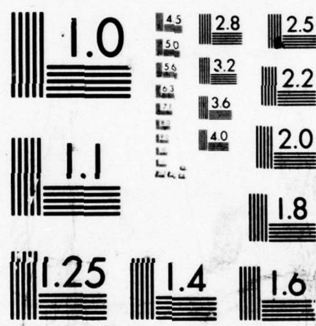
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# FINAL REPORT

## OFFICE OF NAVAL RESEARCH
## CONTRACT N00014-76-C-0514

31st October, 1977



J.W. Goodman

Stanford Electronics Laboratories
Stanford University
Stanford, California

(6) FINAL REPORT

OFFICE OF NAVAL RESEARCH

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(10) J.W. Goodman

Stanford Electronics Laboratories
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## I. INTRODUCTION

Contract N00014-76-C-0514 and its predecessor, contract N00014-67-A-0112-0023, have provided research support for Professor Joseph Goodman and his students for a period of ten years. The research performed under the contracts has spanned the fields of image formation, optical information processing, and holography.

In this final report on the contracts, we first summarize the research accomplishments of the past contract year (section II). Attention is then turned to an overview of the accomplishments of the entire ten years of support (section III). Included are short discussions of the general subjects investigated, a list of the students supported by the contracts and their current professional positions, and finally a list of the publications reporting on work supported in part or in entirety by the contracts.

## II. ACCOMPLISHMENTS OF THE PAST YEAR

Major emphasis during the past year has been on the development of new methods for extremely fast, fully parallel, incoherent optical data processing systems. While most coherent optical data processors require information to be input onto a real-time (electronic or electro-optic) transparency in a serial or time-sequential fashion, incoherent processors offer the possibility of fully parallel data input at enormous speeds.

The particular approach to incoherent optical processing formulated and partially demonstrated by us during the past year is summarized in the Appendix, which is a pre-print of an article to appear in Optics Letters in January 1978. We believe that the utilization of

modern opto-electronic technology (including LED's, laser diodes, fibers, and fast photodetectors) in optical signal processors holds enormous potential for the future, and we hope that our initial work in this area, as carried out under ONR sponsorship during the last year, will lead to a new family of optical processors with unique and useful properties.

## III. OVERVIEW OF THE ACCOMPLISHMENTS OF THE PAST TEN YEARS

### A. Areas of Research

(1) Holographic Imaging through Atmospheric Turbulence.

The first area of research supported by this contract concerned the effects of atmospheric turbulence on holograms and holographic images formed over long propagation paths. The research consisted of both analytical studies, using the Tatarski theory of propagation through turbulence, and experimental studies of the effects of the atmosphere on fringe formation over long outdoor paths. The research culminated in two publications in the Journal of the Optical Society of America. One graduate student was supported for this work, and he received his Ph.D. degree with his thesis on this subject matter.

(2) Digital Image Formation from Holographic Data

In 1968 we undertook a research project on the formation of images from detected holographic data by means of digital computation. The prime area of application was anticipated to be acoustic holography, for which a decision between optical image formation and digital image formation was a very real one. We were successful in producing the first digitally reconstructed

images from real holographic data. In addition, a theoretical study led to the first analytical understanding of the effects of Fourier-domain quantization on holographic images. Three publications resulted, and one student received the Ph.D. degree based on this work.

(3) High Efficiency Volume Holograms

During 1968 and 1969, we undertook a theoretical study of the efficiency with which thick holograms transfer light to their reconstructed images. While a theory published earlier had dealt with the theory of thick holograms consisting of a single sinusoidal component, our studies concerned the case of multiple stored sinusoidal gratings. A paper on this subject was presented at a meeting of the Optical Society of America, and a student received the Ph.D. degree based on his thesis in this area.

(4) Pre-Detection Image Processing for Enhanced Image Restoration

In 1970-1971 we explored a number of possible ways to modify the pupil of an optical system in order to make the detected images more amenable to post-detection image enhancement. This work pointed out for the first time that, if images are expected which have been subjected to a known degradation (e.g., a focusing error), a proper apodization of the imaging pupil can result in a detected image which is especially well suited to post-detection restoration. The work resulted in a publication and one student received his Ph.D. based on this work.

(5) Low-Light-Level Limitations in Fringe Measurement and in Image Restoration

In 1970 and 1971, a study of the photon-limitations to fringe-parameter measurement was undertaken. The work was motivated by the interest that then existed in a variety of optical array techniques for image enhancement, all of which required the accurate measurement of fringe parameters at low light levels. A comprehensive theory was successfully developed. In addition, the study included an examination of the photon-noise limitations of image enhancement. The results of these studies were published, and one student received his Ph.D. degree with a thesis in this area.

(6) Space-Variant Digital Restoration of Images

In 1972, a study of the types of image degradations introduced by relative motions of a camera and the subject being photographed was undertaken. Rather complicated space-variant blurs were found to exist. A new method for restoring such blurred images was developed and demonstrated. Since the blurs encountered are space-variant, straightforward Fourier domain restoration procedures could not be applied, and more sophisticated approaches were found to be necessary. The work resulted in several publications and a Ph.D. thesis.

(7) Restoration of Degraded Images Formed in Partially Coherent Light.

The problem of restoring degraded images formed in partially coherent light is an extremely difficult one, due to the non-

linear nature of the image forming process in this case. In 1973 we developed a new approach to this problem and demonstrated its feasibility experimentally. A considerable amount of new theoretical understanding of the image forming process was developed during the course of this work. The results were published, and one student received his Ph.D. based on his thesis in this area.

(8) Computer Generated Spatial Filters with High Light Efficiency

During 1973 and 1974, we developed several new methods for constructing computer-generated spatial filters with high light efficiency. Several of these methods were demonstrated experimentally. A Ph.D. thesis on this subject resulted.

(9) Laser Speckle

During 1975 we published two new theoretical results pertaining to laser speckle. One was the first analytical derivation of the intensity statistics that result from the addition of N partially correlated speckle patterns. The second was an analytical derivation of the intensity statistics obtained in a speckle pattern generated by a surface which has a roughness that is smaller than a wavelength. Following these publications, we prepared a review article on the statistics of laser speckle patterns. This article is now one of the standard references in the field.

(10) Nonlinear Optical Data Processing

During the years 1973-1976 we developed new methods for

performing nonlinear optical data processing operations using coherent optical systems. These methods are based on the use of half-tone-screen encoding processes. The work had sufficient impact to motivate a number of other research groups in the U.S. and abroad to continue efforts along these lines based on our early publications. Our work included methods for realizing logarithmic transformations, analog-to-digital conversion, and pseudo-color picture encoding. Approximately six publications resulted from this work.

(11) Incoherent Matrix-Vector Multiplier

This work has begun in 1977, and is reported on in detail in the Appendix.

In addition to the above research areas specifically funded by our ONR contracts, several other research areas were initiated with the help of this contract, and then funded for more in-depth research by other agencies. These areas include:

Interferometric imaging methods for astronomical imaging through turbulence (NSF);

Computer generated holographic memories (NSF); and

Space-variant optical data processing systems (NSF).

Four students received their Ph.D's under these latter research efforts.

B. <u>Students Receiving Ph.D's with Partial or Total Support from our ONR Contracts</u>

1. NAME: Jack D. Gaskill (total support)

Thesis title and date: "Holographic Imaging Through a

Randomly Inhomogeneous Medium", May 1968.

Present position: Administrator for Academic Affairs and Professor of Optical Sciences, Optical Sciences Center, University of Arizona, Tucson, Arizona.

2. NAME: Antonio Silvestri (total support)

Thesis title and date" "Digital Image Formation and Fourier Domain Quantization", May 1971.

Present position: Project Leader, Electromagnetic Systems Laboratories, Inc., Sunnyvale, Ca.

3. NAME: Richard A. Baugh (partial support)

Thesis title and date: "High-Efficiency Volume Holography", June 1969.

Present position: Staff Scientist, Hewlett-Packard Co., Cupertino, Ca.

4. NAME: F. Donald Russell (partial support)

Thesis title and date: "Predetection and Postdetection Filtering for Improved Resolution in Optical Systems", August 1970.

Present position: Manager, Ford Aeronutronic, Palo Alto, Ca.

5. NAME: John F. Walkup (total support)

Thesis title and date: "Limitations in Interferometric Measurements and Image Restoration at Low Light Levels", July 1971.

Present position: Associate Professor of Electrical Engineering, Texas Tech University, Lubbock, Texas.

6. NAME: A.A. Sawchuk (partial support)

Thesis title and date: "Space-Variant Image Motion Degradation", June 1972.

Present position: Associate Professor of Electrical Engineering, University of Southern California, Los Angeles, Ca.

7. NAME: Mete Severcan (partial support)

Thesis title and date: "Computer Generation of Coherent Optical Filters with High Light Efficiency and Large Dynamic Range",

Present position: Instructor, Middle East Technical University, Ankara, Turkey.

8. NAME: Kalyan Dutta (total support)

Thesis title and date: "Sampling and Restoration of Images Formed in Partially Coherent Light", December 1974.

Present position: Staff Scientist, Block Engineering, Cambridge, Mass.

C. Publications on Work Supported in Part or in Whole by our ONR Contracts

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9. J.W.Goodman, "Use of a Large Aperture Optical System as a Triple Interferometer for Removal of Atmospheric Image Degradations", Evaluation of Motion Degraded Images, NASA publication SP-193, 1969.

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34. J.W.Goodman, "Coherent Optical Image Deblurring", invited lecture, International School of Quantum Electronics: Coherent Optical Engineering, Tuscany, Italy, September 1976, to be published by North-Holland Publishing Co.

35. J.W.Goodman, A.R. Dias, and L.M. Woody, "A Fully-Parallel, High-Speed Incoherent Optical Method for Performing Discrete Fourier Transforms", accepted for publication in Optics Letters.

## IV. CONCLUDING REMARKS

The Principal Investigator for this contract, Professor Joseph W. Goodman, would like to express his personal thanks to the Physics Branch of the Office of Naval Research for their support over the past ten years. This contract has contributed enormously to his own professional growth, and has further provided partial or full support for eight graduate students at the beginning of their respective professional careers. We believe that the research accomplished under the contract has had major impact on several different areas of physics and engineering.

The freedom afforded to the Principal Investigator to select and pursue those research efforts he perceived to be of major importance is especially appreciated.

## APPENDIX

# A FULLY-PARALLEL, HIGH-SPEED INCOHERENT OPTICAL METHOD FOR PERFORMING DISCRETE FOURIER TRANSFORMS*

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An incoherent optical data processing method is described which has the potential for performing discrete Fourier transforms of short length at rates far exceeding those afforded by both special purpose digital hardware and representative coherent optical processors.

*Work supported by the Office of Naval Research.

We report here on an incoherent optical method for performing discrete Fourier transforms (DFT's) which has the potential for extremely high data throughput rate. The DFT operation may be viewed as a process of multiplying an input vector $\vec{f}$ (consisting of N possibly complex-valued input samples) times an N×N matrix $\underline{H}$ (the $n,m^{th}$ element being $\exp(-j2\pi nm/N)$) to yield an output vector $\vec{g}$ (consisting of the N complex Fourier coefficients); thus we desire to perform

$$\vec{g} = \underline{H}\vec{f} . \qquad (1)$$

Two separate issues must be addressed in describing the method of interest here: (1) How do we perform the matrix product in a highly parallel and fast way? (2) How do we perform complex arithmetic using incoherent light, for which only non-negative and real quantities (intensities) can be manipulated.

To address the first issue, suppose that the elements of $\vec{f}$ and $\underline{H}$ are non-negative and real. Then the system shown in Fig. 1 can be used to perform the matrix-vector product. The elements of $\vec{f}$ are entered in parallel by controlling the intensities of N light emitting diodes (LED's). Lenses $L_1$ and $L_2$ image the LED array horizontally onto the matrix mask M, while spreading the light from any single LED vertically to fill an entire column of the matrix mask. Lens $L_3$ is a field lens. The matrix mask M consists of N×N subcells, each containing a transparent area proportional to one of the matrix elements. Lens $L_4$ is a cylindrical lenslet array, which is not essential to the operation of the system, but which can be used to improve light efficiency. Lens combination $L_5$ collects all light from a given row and brings it to focus on one element of a vertical array of N photodetectors. Each photodetector

measures the value of one component of the output vector $\vec{g}$.

To permit the multiplication of a matrix $\underline{H}$ with complex elements times a vector $\vec{f}$ with complex elements, we decompose each of these quantities as follows[1,2]:

$$\vec{f} = \vec{f}^{(0)} + \vec{f}^{(1)} \exp(j2\pi/3) + \vec{f}^{(2)} \exp(j4\pi/3)$$
$$H = \underline{H}^{(0)} + \underline{H}^{(1)} \exp(j2\pi/3) + \underline{H}^{(2)} \exp(j4\pi/3) \tag{2}$$

where $\vec{f}^{(0)}$, $\vec{f}^{(1)}$ and $\vec{f}^{(2)}$ consist of N real and non-negative elements each, and $\underline{H}^{(0)}$, $\underline{H}^{(1)}$ and $\underline{H}^{(2)}$ consist of N×N real and non-negative elements. If the output vector $\vec{g}$ is similarly decomposed, then we find that the overall matrix-vector product can be expressed as

$$\begin{bmatrix} \vec{g}^{(0)} \\ \vec{g}^{(1)} \\ \vec{g}^{(2)} \end{bmatrix} = \begin{bmatrix} \underline{H}^{(0)} & \underline{H}^{(2)} & \underline{H}^{(1)} \\ \underline{H}^{(1)} & \underline{H}^{(0)} & \underline{H}^{(2)} \\ \underline{H}^{(2)} & \underline{H}^{(1)} & \underline{H}^{(0)} \end{bmatrix} \begin{bmatrix} \vec{f}^{(0)} \\ \vec{f}^{(1)} \\ \vec{f}^{(2)} \end{bmatrix} . \tag{3}$$

Thus complex operations can be performed at a price of a factor of three in the length of the input and output vectors.

Simple electronic circuits for producing the components $\vec{f}^{(0)}$, $\vec{f}^{(1)}$ and $\vec{f}^{(2)}$ from $\vec{f}$ exist[1], as do likewise simple circuits for producing the real and imaginary parts of $\vec{g}$ from $\vec{g}^{(0)}$, $\vec{g}^{(1)}$ and $\vec{g}^{(2)}$.

Experiments have been carried out to verify the ability to perform complex arithmetic. The source was an unfiltered, linear filament, clear envelope, incandescent bulb. The 30×30 matrix mask used to perform a 10-point DFT is shown in Fig. 2. This mask is designed so that the three entire vectors $\vec{f}^{(0)}$, $\vec{f}^{(1)}$ and $\vec{f}^{(2)}$ are entered side by side,

whereas the three output components $g_k^{(0)}$, $g_k^{(1)}$ and $g_k^{(2)}$ for the $k^{th}$ Fourier coefficient appear side by side. Thus the output display shows each DFT component as a triplet of real and nonnegative components.

For this experiment the input functions were entered by hand as masks placed against the matrix mask, and output functions were detected on a 1024 element Reticon CCD detector array. Figure 3 shows both theoretical output distributions and experimentally obtained output distributions, the latter being photographed from an oscilloscope display. In parts (a) and (b), the function to be transformed consists of the sequence (1,0,0,0,0,0,0,0,0,0). The resulting DFT should be entirely real and of constant magnitude. As shown in these figures, the DFT components along the real axis are all non-zero and equal, while the componenents along 120° and 240° are all zero.

In parts (c) and (d), the input sequence was entirely real and constant. The DFT consists of a large real zero-frequency component (on the far right), followed by triplets of equal strength for all other DFT components. Some thought shows that any DFT component with elements $g_k^{(0)}$, $g_k^{(1)}$ and $g_k^{(2)}$ exactly equal is equivalent to a zero result. Hence all DFT components, except the zero frequency component, are zero.

Parts (e) and (f) show the results when the entire matrix mask is uniformly illuminated. In this case some thought shows that the input is effectively a sequence containing all zeros. The output DFT shows triplets of equal strength, or a sequence of all zeros for the output.

A system composed of 96 high speed LED's and 96 avalance photodiodes would be capable of performing a 32-point DFT. Commercially available components have sufficient bandwidth, output power and sensitivity

to permit such a DFT to be performed every 10 nanoseconds. The total throughput rate for such a processor is about $3\times10^9$ complex samples per second, while a corresponding number for special-purpose digital array processors is about $3\times10^5$ complex samples per second, and a representative coherent optical processor[3] has a throughput of $3\times10^7$ real samples per second.

The chief significance of this processor is that the input data can be entered in parallel, and it is this fact that leads to its high throughput rate. Another system recently described[4,5] performs a similar matrix-vector product, but the data must be entered serially, and as a consequence the throughput rate is much lower. The processor described here is especially well suited for problems in which the elements of the input vector $\vec{f}$ are gathered by parallel sensors. Of course, matrices other than the DFT matrix can also be used if desired.

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2. If one is sufficiently clever in eliminating unwanted terms at the output, real and imaginary components on biases can be used. However, the dynamic range of the system is reduced by such an approach.
3. We refer specifically to a system with an electron-beam addressed DKDP input light valve, which is capable of entering $10^6$ data points 30 times per second. See D. Casasent, Proc. IEEE, 65, 143 (1977).
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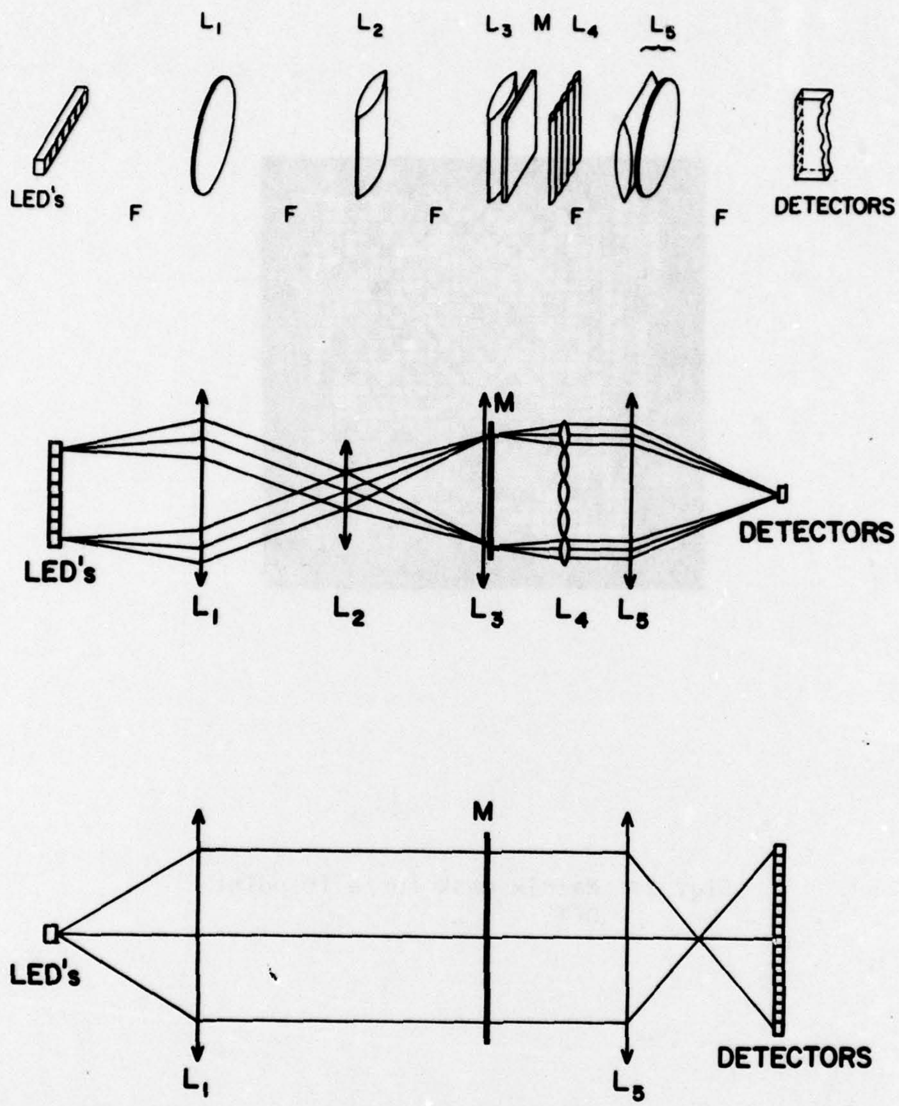


Fig. 1: Incoherent optical processor configuration. (a) pictorial view, (b) top view, (c) side view.

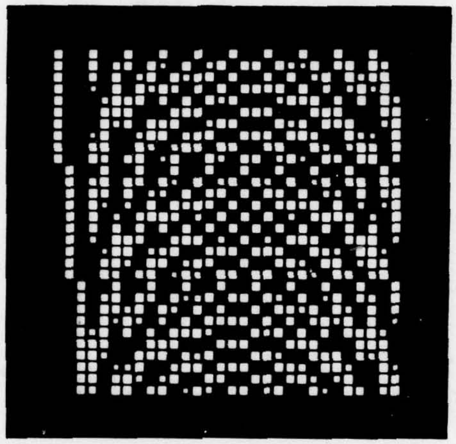

Fig. 2: Matrix mask for a 10 point DFT.

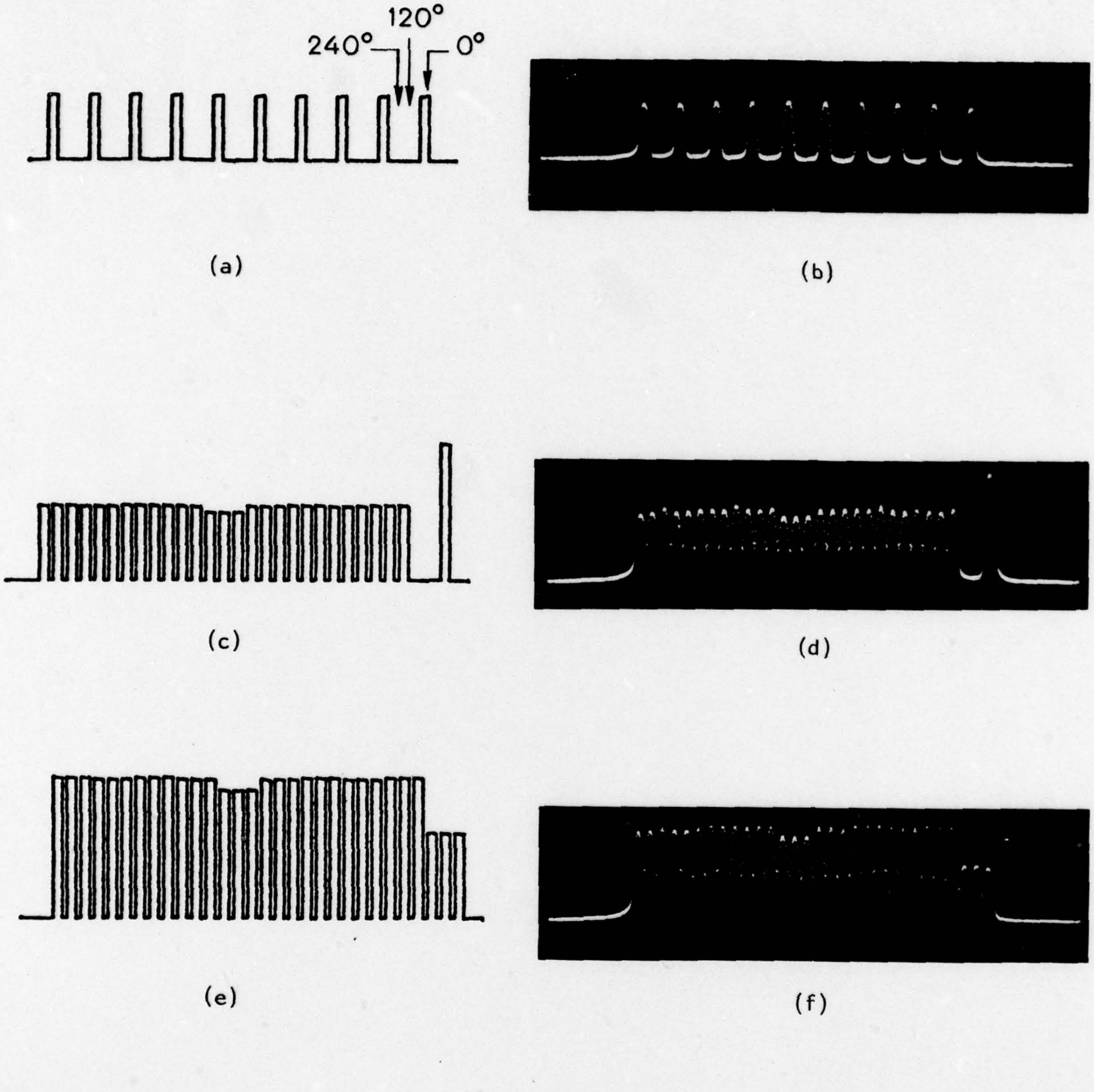


Fig. 3: Theoretical (a,c,e) and experimental (b,d,f) DFT results

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